Increasing Accessibility to Medical Robotics Education

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Abstract—To overcome existing barriers in medical robotics education, this paper presents work done during a joint-collaboration project that creates a new educational toolset and associated curriculum for demonstrating telesurgery applications. Created using the LEGO MINDSTORMS NXT robotics set, programmed with LabVIEW, and capable of doing real-time closed-loop control over large distances, the project team developed a product aimed at influencing 6th to 8th grade classrooms by exposing the students to engineering design and communication topics within the real-world application of medical robotics.

Keywords—medical robotic; LEGO; telesurgery

I. INTRODUCTION

Certainly developments in robotics, computer technology, and their combination have allowed the field of telerobotics to flourish, assisting missions in other areas leveraging such technologies, such as military, space exploration, search and rescue, etc. Medical robotics is another field directly being affected by these advances, as indicated both the increase in telesurgery operations and the rapidly growing market for surgical robot systems. Despite the many advantages these systems provide over traditional human-controlled procedures, several factors are limiting the potential of the field. Reducing these barriers in the next several years will result in directly facilitating further growth in this area. These aspects range from the complexity of the systems involved, the shortage of design and human-factors engineering in this growing field, a lack of specialized scientists and researchers in the pipeline, and general population misconceptions regarding the use and potentials of such tools.

Presented here are details of an on-going project aimed at developing a medical-robotics educational platform and associated curriculum. Creating a simplified system for education and training on the topic of medical robotics, and providing it as a classroom resource, many of the associated barriers can be addressed simultaneously. The research team was charged with the goal of developing a system capable of low overhead costs, in-class deployment, ease-of-use, and ultimately, the capability for mass exposure to and education of telerobotics, telemedicine, and telesurgery concepts for a wide age-range of learners. An iterative design was employed by the cross-disciplinary team to prototype, test, and establish the hardware components, associated software and control algorithms, and a set of guiding pedagogy principles and example activities for assisting with the introduction of these devices and concepts into the classroom.

The paper is organized as follows. Section II provides Background both on the need within the field of medical robotics, but also the educational theory behind developing hands-on robotics systems for use in teaching within classrooms. The section after that briefly covers the Project Goals including both the objectives and the requirements of the project. In Section IV a breakdown of the system components is examined from the perspective of the Design Process before the entire final System Description is given in Section V. Finally Section VI concludes the paper with final remarks and future directions in which this research is headed.

II. BACKGROUND/NEED

A. Medical Robotics

Advances in robotics and computer technology have enabled much complex work to be achieved via remote control. Using such technologies, telerobotics enables surgery to be performed over long distances, as demonstrated by the first transatlantic procedure in 2001 executed by Dr. Marescaux in Strasbourg, France. In the U.S. alone, the market for medical robotics and computer assisted surgery equipment was worth an estimated $648 million in 2008 and is projected to reach $1.5 billion by 2014, with surgical robot systems as the largest product segment (54% market share in 2008) and is expected to increase to 65% by 2014 as [1]. The potential advantages of robotic surgical systems over human-controlled surgical procedures include increased degrees of freedom for manipulation; elimination of the fulcrum effect in minimally invasive surgery; reduction of tremors that the surgeon may have; motion scaling to increase accuracy; reduction of fatigue; restoration of depth perception and haptic (tactile and kinesthetic) perception; automation of basic surgical tasks; and potentially enabling the performance of complex procedures not previously possible. More importantly, the expected advantage of using robotics for telesurgery is the potential to save lives remotely, reducing both the need for travel and the time delay in receiving treatment.

Even with these potential advantages and the projected market growth of telerobotics for surgery, poor technology...
design and implementation, often due to poor understanding of human factors issues, remains a major problem. For example, the problem of managing communication outages, delays, and bandwidth variation during the transfer of data between the master control (surgeon site) and the telemanipulator (patient site), and the lack of haptic feedback from the robotic arm impose a high cognitive and physical demand on the surgeon. With these systems, the surgeon must learn a new set of tools and visual motor control skills and operate in a workspace with fewer degrees of freedom [2]. Effective teleoperated systems require both technical solutions and human factors engineering.

Public acceptance of telerobotics in healthcare is lacking as well. Stemming from a larger opinion towards the field of robotics (and conceptions/misconceptions of the future of that field) in combination with varied public views of medical professionals and the role they play, much misinformation and as a result negative attitudes exist. While marketing and PR from related industry representatives are certainly working to change this, other forces, most notably the influence of media hype and Hollywood imagination and dramatization, often plant images in people’s minds that are difficult to overcome. For robotics in general, and robotic technology in medicine/surgery specifically, while the portrayed advanced systems are employed with best intentions in mind, they often play the role of the antagonist in the movie representation. For both wider acceptance and use by the public and to ensure positive excitement in the field (thus encouraging our next generation of scientist and researchers), a fundamental change in attitude and aptitude to understand and appreciate medical telerobotics also needs to happen.

B. Educational Theory

Development psychology pioneer Jean Piaget’s commentary on teaching described manipulating artifacts as key to students constructing knowledge. Piaget’s theory of constructivism described learning through actions. Learning, according to Piaget, involves constructing new knowledge out of existing knowledge by manipulating artifacts and observing their behavior [3]. This concept has been extended by the work of Seymour Papert and others and has led to the formation of the LEGO® MINDSTORMS Robotic Systems. The robots themselves serve as the artifacts students need to construct knowledge. One aspect of robots that make them a useful teaching tool is the way they interact with their surroundings. Students can observe how environmental aspects interact with the robot and construct knowledge about that interaction [4].

Beyond just the observational aspects of interacting with a robotics system, leveraging a robotics toolset where the students themselves are the ones being able to design, build, test and redesign provides an additional level of engagement. Adding touch to the educational process, among the other senses, forms the kinesthetic modality [5]. Teaching with robotics uses the Kinesthetic modality by including physical objects which can be held and moved. Traditional training for military and medical purposes has long taken advantage of the kinesthetic modality, employing simulators with controls requiring realistic levels of force as well as digital visual interfaces. This training, which is body-centered, develops kinesthetic memory that is a human being’s ability to remember the position of their limbs [6]. Thus, teaching with robotics, specifically as demonstrated here in the field of medical robotics, builds further on this tradition. Real demonstrations of physical phenomena, including the tactile experience provided by allowing the students direct interaction with the material, results in knowledge constructed by the students [7].

III. PROJECT GOALS

A. Objectives

To address these need for a next-generation medical robotics education platform accessible by a large range of students, a new project at Tufts University in Massachusetts USA in collaboration with Ecole des Mines de Nantes in France has been launched aimed at the education of the broader public, and especially school-age children, in the concept of medical telerobotics. With a primary goal of exposure and engagement towards this general field, and a secondary one of filling the pipeline of trained engineers interested in telerobotics for medicine, a team of interdisciplinary graduate students has been formed (with backgrounds in mechanical engineering, computer engineering, electrical engineering, engineering management, human factors, and cognitive psychology). Working together, albeit remotely across the Atlantic, the students on both campuses were tasked with the challenge of building an “education friendly” prototype for a teleoperated robotic surgical system.

B. Requirements

System requirements dictated that the product be inexpensive (thus, accessible to many classrooms), kid-friendly and safe, easy to transport/setup/control, allow local and remote manipulation, and age-scalable (adaptable to primary, secondary, and university level settings). Finally, an associated curricular outline needed to be conceived to fit with existing classroom standards and current material being taught in order to facilitate eventual widespread educational adoption.

Stemming from the educational theory driving hands-on project-based learning, further requirements were incorporated to enhance the classroom experience and to shape the curriculum. Essential was a flexible platform allowing mixed-group use. To facilitate classroom management, and scaffold the teachers’ learning continuum, the system needs three modes of group interactions: single pairs interacting directly with the software/device, in-class groups interacting with each other, multiple cross-class groups remotely located sharing and collaborating. Further, developing a system targeting a specific age range of learners may be affective for instigating change at that level, but fails to provide access to those earlier or provide multi-tiered educational opportunities for those either entering a program later or progressing on for follow-up studies. Thus, an adaptable pedagogy that addressed the needs of a diverse age group was necessary.

After consideration and preliminary investigation of alternative platforms, the LEGO NXT MINDSTORMS robotics toolset was selected as the platform for the initial iterations of prototype design and testing. The LEGO kit consists of an NXT programmable brick with four sensor ports and three actuator ports, providing the research team a base set
of technology for adequate connectivity required for advanced teleoperation and control yet accessible to a wide range of learners (this kit can be found in classrooms ranging from middle-primary through university level age ranges). A graphical programming language (the LabVIEW environment) was selected as the software interface, where a combination of front-panel interfaces, high-level blocks, and exposure to low-level functions allowed a scalable interface for users during introduction to these digital robotic control concepts.

IV. DESIGN PROCESS

An iterative design process was used. Four areas for design efforts were identified: teleoperator end-effector, force feedback, teleoperation and control, and pedagogy. The design process employed for each is described briefly here.

A. Teleoperator End-Effector

Using only LEGO pieces as the building blocks, the end-effector for the teleoperated system could take the intuitive form of a two-element grasper, a three-fingered segmented hand, or a cradle. Early iterations of the design (see Figure 1) included a single-point extension, representative of needle insertion. By keeping the robotic design modular, this allowed a certain flexibility of components where different end-effectors could be substituted independent of the other modules, in a response to changing environmental, classroom, or curricular needs (e.g. variations to level of difficulty might include a more sophisticated system, thereby challenging advanced students further).

Figure 1. LEGO CAD model of early robotic arm design

B. Teleoperation and Control

Teleoperation and control is dependent on the quality/bandwidth of the telecommunication channel. While in-classroom options between adjacent devices may be more robust, for effective teleoperation across the Atlantic (the ultimate test-case for this project, since the two design teams were remotely located), this is especially important. Thus, artificial lag representing estimated final deployment conditions was introduced even during early on-site preliminary development. Additional practical considerations, such as wired or wireless connectivity and portability for the classroom environment, were examined during the design process and ultimately shaped the final system.

The teleoperation design utilizes a master-slave configuration, in which a controller (the master) reads commands from the human operator and sends them to the robot at the remote site (the slave) to execute. It consists of several components: a controller, communications module, and feedback interface. In development of a suitable controller, several possible interfaces were explored for allowing the master user to manipulate the system, including pure software solutions (virtual dials and buttons representing possible actions), to off-the-shelf commercial robotic arms, to creating a full duplicate robot. For communication, several different technologies were leveraged to get one robot to talk to the other: USB direct connect, Bluetooth short-range wireless, 802.11x wireless, and Ethernet communications. Similar to the end-effector, by modularizing the different components, each could be swapped in or out depending on the most appropriate tool needed at any particular time (for instance, based on classroom setup or available resources). Finally, to incorporate feedback to properly create the close-loop system, options from virtual (again, indicators on the screen) to visual (video display) to force-feedback (describe in more detail in the following sub-section) were explored.

C. Force Feedback

To improve control in telemanipulation, haptics (or force feedback) were incorporated into the system. Haptics are an important sensory input in surgery (traditional as well as robotic), allowing for the realization of the tissues and organs. Reduced haptic feedback, such as in minimally invasive procedures, may lead to excess force being applied in tissue handling, resulting in tearing. It may also contribute to longer procedure times as well as increased cognitive load [8]. The lack of haptics in robotic surgery can lead to increased operation times, longer learning curves, and more surgical errors. Visual feedback, such as 3D vision combined with the surgeon’s ability of detect visual cues (such as damaged tissue) may help to compensate for this to some degree [9]. In determining the appropriate level of feedback for the user in the system being presented here, initial tests with visual indicators were tested (a la [8] where graphical user interfaces, such as LED bars representing force feedback levels, have been implemented). But it was determined that force feedback involving real forces was needed, where the user actually feels equivalent physical reactions. To achieve this, design alternatives examined the sensing mechanisms (sensors/hardware) and associated software control and manipulation.

D. Pedagogy

When designing the lesson plans, early explorations looked at using the same toolset designed above (the hardware and software components) but scaffolding it for different age ranges through a series of related activities. Using the grade-specific tiered “Characteristics of Investigations” that students develop at different age ranges (presented in Table 1, paraphrased from [10]) the different types of curricular components could be developed for a medical robotics related activity.
V. SYSTEM DESCRIPTION

The systems components for the local and remote subsystems are identical. They consist of a LEGO NXT controlled robot, a LabVIEW control interface and instrumentation, a video camera for live video capture and transmission. The final design for the teleoperator end-effector was selected based on physical limitations of weight and control (Figure 2). The two-element grasper was selected to optimize the large operating forces on the teleoperator with three motors, while being able to pick and place relatively large objects (such as a LEGO ball as shown in the figure).

The end-effector can be controlled and teleoperated by a human operator, who manipulates a replicate of the grasper on the master via a control box through closed loop control.

Table 1. Characteristics of Investigations by grade level and potential Medical Robotics activities

<table>
<thead>
<tr>
<th>Grade</th>
<th>Characteristics of Investigations (from Massachusetts Curriculum Frameworks [10])</th>
<th>Medical Robotics Example Activity Components</th>
</tr>
</thead>
<tbody>
<tr>
<td>PreK-2</td>
<td>Students ask questions, make observations, and communicate about what they observe. They follow teacher’s investigation directions and write down what happens over time in their own words.</td>
<td>Teacher led demonstration of the robotic arm and remote control, followed by classroom discussion of characteristics and attributes of system.</td>
</tr>
<tr>
<td>3-5</td>
<td>Students plan and carry out investigations over several class lessons. Teacher first models process of selecting question, formulating a hypothesis, planning the steps, determining objective way of testing. Students incorporate mathematical skills of measuring and graphing.</td>
<td>Teacher asks a series of “what if” questions related to the robotic arm and telecommunications, pushing the students to first theorize and then test out the inquiries on the physical device.</td>
</tr>
<tr>
<td>6-8</td>
<td>Teacher guides, but allows more variation in student approach. Students control variables in test, and work becomes more quantitative and run multiple trials/measurements to minimize sources of error. At conclusion, students prepare reports of questions, procedures, and conclusions.</td>
<td>Students, working in smaller groups, are allowed “free play” experimentation with the robotic arm system, and then issued challenges where they must collaborate across groups to find solutions to simple communication problems and test scenarios.</td>
</tr>
<tr>
<td>High School</td>
<td>Students design and carry out experiments, working alone or in small groups, coming up with questions and hypotheses. Encouraged to carry out extended independent experiments that explore scientific hypotheses in depth.</td>
<td>Challenges and scenarios with more precise movements, programming the robotic arm, and explorations of more advanced concepts and the mathematical theories behind the system.</td>
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Figure 3 shows the architecture of the communications scheme, specifically highlighting the transatlantic communication setup.

To incorporate force feedback into the system (beyond the visual feedback provided by the video camera and camera view components), grasping forces are estimated by sampling the velocity using the joint motors of the teloperator arm, and transmitting a value of power (through a lookup table) back through the system to the master arm motors. This allows the user controlling the master system to detect and feel, in real time and as part of the closed-loop system, the force feedback.

For this iteration of the project, the focus of the team was on developing activity curriculum for the 6-8th grade age range. This was chosen in order to focus the team’s efforts on one
initial set of activities in addition to leveraging available classrooms that the Tufts CEEO group had access to in order for testing. According to [10], in Table 2 is listed the Content of Each Learning Standard for the “Engineering Design” and “Communication” topics for grades 6 to 8. These two topics were selected due to their direct relevance to the robotic arm designed. By directly addressing the points discussed in these two standards, while the topic of “medical robotics” is not one directly covered within the current classrooms, by highlighting these standards within the activities the process of incorporating the work into the teachers’ classrooms is facilitated and the real-world context is directly demonstrated for the students. Preliminary testing of the classroom activity was performed with first-year French university systems engineering students. Even though the target audience was not the intended population, valuable feedback was obtained which will allow for further refinement. This exercise emphasized the importance of pilot testing with the end-users of the product.

Table 2. Content of Each Learning Standard (Massachusetts) for Grades 6 - 8 [10]

<table>
<thead>
<tr>
<th>Engineering Design</th>
<th>Communication</th>
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</thead>
<tbody>
<tr>
<td>1. Steps of the engineering design process</td>
<td>1. Components of a communication system.</td>
</tr>
<tr>
<td>2. Methods of representing solution to a design problem.</td>
<td>2. Appropriate tools, machines, and electronic devices used to produce and/or reproduce design solutions.</td>
</tr>
<tr>
<td>3. The purpose of a prototype</td>
<td>3. Communication technologies and systems.</td>
</tr>
<tr>
<td>4. Appropriate materials, tools, and machines to construct a prototype.</td>
<td>4. How symbols and icons are used to communicate a message.</td>
</tr>
<tr>
<td>5. Design features and cost limitations affect the construction of a prototype.</td>
<td></td>
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<tr>
<td>6. The five elements of a universal systems model.</td>
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</tbody>
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VI. CONCLUSIONS AND FUTURE WORK

This work described the design and creation of a robotic arm for demonstrating medical robotics applications (related to telesurgery) and an associated activity set for bringing the system into 6-8th grades. With design requirements ranging from low-cost, ease-of-use, and taking into consideration communication constraints such as cross-Atlantic channels, the final LEGO NXT creation programmed with LabVIEW demonstrated the feasibility of such a system and the potential for using this type of toolset for incorporation into the school curriculum. Future work involves robust testing of the feedback control loop under varying circumstances (such as unexpected loss of signal, etc), more extensive classroom testing, and general expanding of the activities to cover other standards (e.g. non-engineering).

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